The Three-Dimensional Power Spectrum Measured from 2MASS

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Abstract. We present the three-dimensional power spectrum of galaxy clustering using measurements of the angular correlation function from the second incremental release of the Two-Micron All Sky Survey (2MASS). The angular positions of galaxies out to a limiting magnitude of $K_s \leq 14.0$ (508,054 galaxies) determine the correlation function. We consider a variety of estimators of the catalog's angular correlation function, and we find the Landy and Szalay (LS) estimator to be the most reliable choice. Using the LS estimator, we find that the angular correlation function takes the form of a power law with a break. The angular correlation function is then used in combination with the selection function to determine the power spectrum by inverting Limber's equation. We find good agreement with previous measurements of the power spectrum for $0.04 \lesssim k \lesssim 0.1h$ Mpc^{-1}, and evidence for a peak in the power spectrum around $k \sim 0.03h$ Mpc^{-1}. For $k \gtrsim 0.1h$ Mpc^{-1} we find that the power spectrum is biased higher than other surveys, which can be understood as a color-based selection effect.

1 Introduction

The power spectrum $P(k)$ is one of the most important statistics characterizing large scale surveys. There are many ways of obtaining the power spectrum. Which method is chosen is mainly dependent on the type of information collected in the survey and the geometry of the survey coverage area. 2MASS is a photometric survey with some spectroscopic follow-ups to help determine the luminosity function; therefore we have mainly angular information and little radial information. We begin by determining the angular correlation function, which is in itself an interesting statistic. We then invert Limber's equation using the method of Baugh & Efstathiou [1] along with the selection function, and determine the three-dimensional power spectrum. Finally, we use a jackknife estimator to determine the bias and errors of the angular correlation function and carry this through the inversion, folding in systematic errors to ultimately estimate the errors in our determination of the power spectrum.

2 Two-Point Angular Correlation Function

The two-point angular correlation function $w(\theta)$ is defined in terms of the joint probability of finding two galaxies (out of a sample of galaxies with angular density $\mathcal{N}$) separated by an angle θ on the sky:

$$\delta P = \mathcal{N}^2 \delta\Omega_1 \delta\Omega_2 [1 + w(\theta_{12})]. \tag{1}$$

In practice one uses an estimator of $w(\theta)$ in order to deal with the fact that the data are points and not a continuous function. There are many standard estimators of the correlation function, all of which rely on a Gaussian random field of points having the same geometry as the data. In using these estimators one determines normalized bin counts of data-data (DD), data-random (DR), and random-random (RR) pairs. In our analysis, we use logarithmic bins of angular separation in the range of $0.05° \lesssim \theta \lesssim 11°$. After testing the standard estimators with a mock catalog having a known angular correlation we find the Landy & Szalay (LS) estimator [7]

$$w_{LS} = \frac{DD - 2DR + RR}{RR} \tag{2}$$

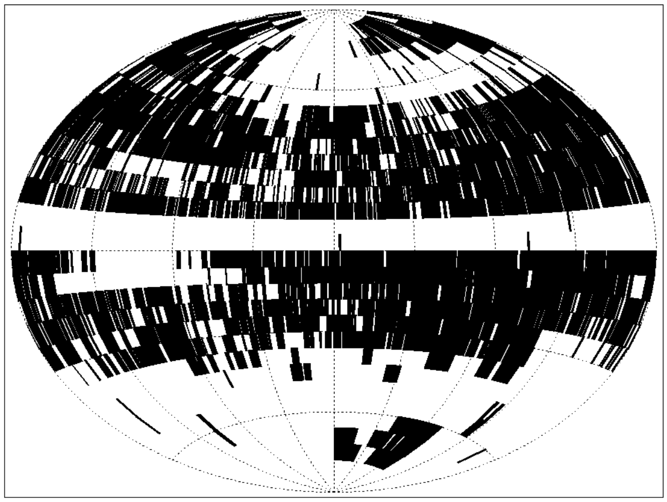

Figure 1: An Aitoff plot in ra and dec of the mask determined from the 2MASS second incremental release catalog. Note that the equator in this plot is not the galactic plane.

performs best at recovering the known correlation with our mask (Fig. 1). Other studies [5] of the standard estimators have also shown the LS estimator to have the least variance.
Figure 1 shows the mask for the galaxies in the 2MASS second incremental release. In order to avoid dust extinction from the disk of the Milky Way we make a cut in galactic latitude. We have calculated the angular correlation with cuts of 10°, 20° and 30° in galactic latitude and have found that these different cuts produce very similar angular correlation functions. Therefore we use the angular correlation with the least conservative cut in order to improve statistics. To further improve statistics we use many random samples with approximately two times the number of random points as data points to determine the angular correlation. The errors we determine for the angular correlation function include Poisson errors in the binning and variance in the angular correlation function from a jackknife resampling analysis.
We determine $w(\theta)$ (Fig. 2a) using a $O(N \log N)$ algorithm which involves an oct-tree decomposition. The calculated $w(\theta)$ is of the expected form, with a power law on small angular scales and a break between 1 and 10 degrees. Using χ^2 fitting we find a power-law fit $\sim \theta^{-0.79}$, for $\theta < 1.7°$. In comparison to APM [1] and the latest angular correlation from SDSS [2], the power laws are similar, but the break is at much larger angular scales than the other two surveys. This is due to the fact that both SDSS and APM are much deeper samples and therefore their angular correlation length is expected to be smaller than that of 2MASS, assuming they have the same three-dimensional correlation functions.

3 Method

Using the angular correlation function in combination with the selection function $\phi(x)$, we need to invert Limber's equation

$$w(\omega) = \int_0^\infty P(k) g(k\omega) k dk, \quad \omega = 2\sin(\theta/2) \tag{3}$$

$$g(k\omega) = \frac{1}{2\pi N^2} \int_0^\infty x^4 \phi^2(x) J_o(k\omega x) dx \tag{4}$$

to determine $P(k)$. Since analytical solutions can only be found for very few special cases, we perform the inversion numerically. In particular, we use an iterative method of inverting eq. 3 which is based on Lucy's original iterative method [8] modified to include non-positive definite kernels as done in ref. [1]. In the algorithm one first makes an initial guess as to the shape of the power spectrum and then convolves this with the kernel, thus obtaining an angular correlation function. One then calculates

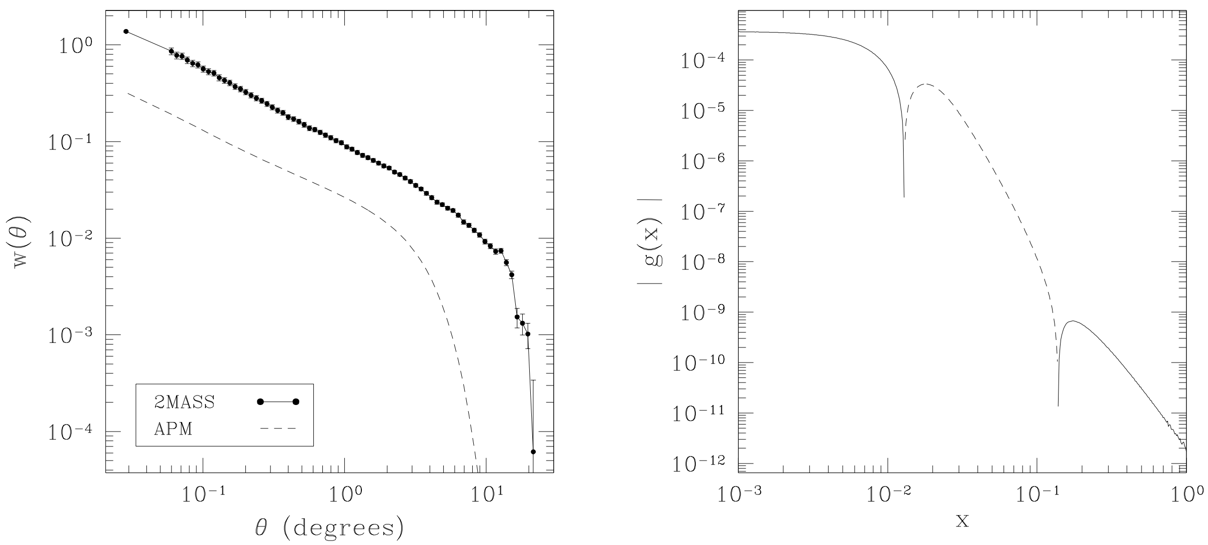

Figure 2: The two-point angular correlation function and kernel from the 2MASS second incremental release. Figure 2a gives the correlation function measured from the sample of galaxies with limiting magnitude $K_s \leq 14.0$. The errors are calculated using a resampling jackknife procedure and include Poisson errors in the binning. Figure 2b is the absolute value of the kernel calculated from the Schechter fit to the 2MASS K-Band luminosity function. In the dashed portion $g(x)$ is negative.

multiplicative corrections to the power spectrum based on the deviations from the measured angular correlation function. This process is then repeated until the power spectrum converges to a stable solution and the computed angular correlation function matches the measured correlation function.

3.1 Kernel

The kernel (eq. 4) in Limber's equation (eq. 3) is determined from the selection function, which is in turn dependent on the luminosity function and completeness. We use the best fit Schechter function parameters from Kochanek et al. [6] for the luminosity function. We ignore redshift effects on the colors as well as deviations from Euclidean geometry because of the shallowness of 2MASS (mean redshift of $z \sim 0.05$). Figure 2b shows a plot of the kernel, where one should note the two zero crossings across the range of $k\omega$ shown. The first zero crossing gives a natural scale for which the inversion process is most sensitive $k\omega \sim 0.016h$ Mpc^{-1}. For a fixed value of ω the integral is most sensitive to values of the kernel near this point. Based on the 2MASS angular correlation function (Fig. 2a), we have sensitivity in the power spectrum down to wavenumbers of order $k \sim 0.04h$ Mpc^{-1} and up to $k \sim 10h$ Mpc^{-1}.

3.2 Tests of Inversion

Tests on mock power spectra with the 2MASS kernel show that the inversion has sensitivity down to $k = 0.02h$ Mpc^{-1}. We find that the stability of the inversion becomes very poor if we extend the range to include smaller wavenumbers. Tests were also performed to determine how well the inversion process is able to recover the angular correlation function. The recovered angular correlation functions agree well with the mock measured angular correlation functions, except in cases were the angular correlation function contains a spike or sharp discontinuity. For this reason we are unable to completely recover the sharp features in the measured angular correlation function (Fig. 2a) in the vicinity of $\theta \sim 10°$. By using an appropriate guess of the power spectrum in the first iteration for all of the test cases, the inversion method is able to converge to a stable solution after only 10-30 iterations. Allowing the iteration to continue to 100-500 iterations yields little change in the resulting $P(k)$ and no improvement in the recovered angular correlation function. Unlike the method presented in [1], we found that there is no need for introducing a smoothing parameter.

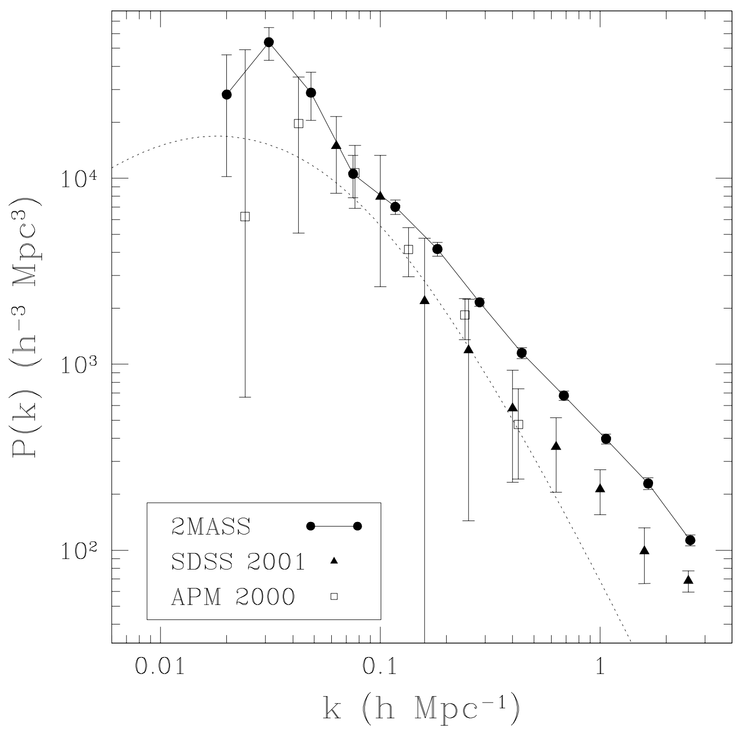

Figure 3: The calculated power spectrum is shown above as filled circles connect by a line. Also plotted are the recently released power spectrum from SDSS and the power spectrum from the most recent analysis of the APM data. The dashed line is a no tilt ΛCDM linear power spectrum with $\Omega_m = 0.3$, $\Omega_b = 0.04$ and $h = 0.72$ using the $\sigma_8 = 0.915$ from [10].

4 Power Spectrum

By applying the inversion method to the 2MASS angular correlation function (Fig. 2a) we obtain the power spectrum shown in Fig. 3. Also shown in Fig. 3 are the power spectra from the APM survey [4] and SDSS survey [3] with a no tilt ΛCDM linear power spectrum with $\Omega_m = 0.3$, $\Omega_b = 0.02$ and $h = 0.72$. The power spectrum we determine from 2MASS shows the typical deviation from linear theory at large values of k, but it is higher than that of APM and SDSS. This difference in the power between APM or SDSS and 2MASS on small scales can be explained as a selection effect. Both APM and SDSS are samples of optically selected galaxies, while 2MASS is an infrared (K_s) selected sample. The selection of 2MASS will tend to pick out more cluster galaxies than APM and SDSS and fewer field galaxies, therefore showing more power on small scales. There is fairly good agreement between the surveys and the model in the wavenumber range of $0.05 \lessapprox k \lessapprox 0.1h$ Mpc^{-1}, but even in this range the 2MASS power spectrum has slightly higher amplitude. This could mean that the power spectrum of 2MASS has a slightly greater overall linear bias than the other two surveys. The relative bias between SDSS and 2MASS is $b \sim 0.7 - 0.8$. It is closer to 0.8 if one tries to fit the model spectrum or on the order of 0.7 if the power spectra are forced to match at $k = 0.252h$ Mpc^{-1}. The most interesting feature of the power spectrum is the very sharp peak at $k \sim 0.03h$ Mpc^{-1}, which is also seen in the APM power spectrum. The error bars on the 2MASS power spectrum may be slightly optimistic, but there is no doubt about the existence of this peak. The width of this peak is inconsistent with linear ΛCDM models and may be showing us a new feature in the power, or possibly a contribution from baryons as claimed by 2dF [9].

The errors on the power spectrum take into account errors from the luminosity function, errors given for the angular correlation function, and estimates of the errors from the inversion technique. The errors from the angular correlation function take into account the Poisson binning errors and variance estimates from a jackknife resampling process. There may be errors introduced by the method used

to determine the angular correlation which have not been accounted for. One sigma errors from the luminosity function are also included. To estimate the errors, we use different values for both the luminosity function and the angular correlation function within their respective errors. We determine a statistically large sample of power spectra using different values of these parameters. From these power spectra, the extreme value for each point is multiplied by a correction factor, determined from the inversion, and is used as the estimated error. The errors for $k < 0.08h$ Mpc^{-1} are small due to the fact that they depend on the angular correlations at small angular separation, which have corresponding small statistical errors. They also seem to have less of a dependence on the errors in the luminosity function. Due to the fact that the peak in the spectrum ($k \sim 0.03h$ Mpc^{-1}) has such small error bars and that there are correlations in the errors due to the technique, the errors on the lowest k point may be slightly underestimated. Based on simulations done with mock power spectra the lowest k point is otherwise believable.

5 Conclusions

In this paper we calculate the two-point angular correlation function for the 2MASS second incremental release and obtain the three-dimensional power spectrum using an iterative algorithm. We find that the 2MASS power spectrum recovered using this method is in good agreement with power spectra from SDSS and APM, as well as model predictions for $0.05 \lesssim k \lesssim 0.1h$ Mpc^{-1}. For $k > 0.1h$ Mpc^{-1} we find that the power spectrum of 2MASS deviates sooner from the modeled linear spectrum and is higher than that of SDSS and APM. This is probably due to color selection. We also find a narrow peak in the power spectrum around $k \sim 0.03h$ Mpc^{-1}, for which there is evidence in APM as well. This could be the result of baryonic oscillations in the power spectrum, or a new feature in the power spectrum which is yet not understood. We plan to repeat this analysis as soon as the full 2MASS catalog becomes available. This will yield better statistics and will not be plagued by possible geometric effects arising from the mask.

Acknowledgements. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and NSF. We thank John Huchra for encouragement, discussions, and help. This research was funded by grants at UCSC from NASA and NSF.

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